CLAIMS

What is claimed is:

1. A method of particle analysis, comprising:

(a) exposing a number of particles in suspension to an incident light with a predetermined time-varying intensity, the particles being sufficiently close to one another to multiply scatter light;

(b) detecting multiply scattered light from the particles in response to the incident light to determine a first value corresponding to an observed isotropic scattering coefficient of the particles;

(c) establishing an estimate corresponding to at least one of volume fraction or size distribution of the particles;

(d) calculating a second value from the estimate, the second value corresponding to a calculated isotropic scattering coefficient;

(e) comparing the first and second values to establish an error;

(f) changing the estimate; and

(g) repeating said calculating, comparing, and changing until the error reaches a desired minimum.

2. The method of claim 1, wherein the incident light includes a number of different wavelengths of light, the first value is determined for each of the wavelengths, and said establishing, said calculating, said comparing, and said changing are performed for each of the different wavelengths.

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3. The method of claim 1, further comprising controlling a process as a function of the estimate and determining the estimate to generally maintain mass balance.

4. The method of claim 1, wherein the estimate corresponds to one of a number of parameters for an expected form of the size distribution.

5. The method of claim 4, wherein the incident light includes a number of different wavelengths of light, the first value is determined for each of the wavelengths, the parameters correspond to a Weibull distribution, and said calculating includes:

(i) establishing a number of particle size increments;

(ii) determining a scattering efficiency and a mean cosine of scattering angle as a function of the wavelengths and the increments; and

(iii) performing a first summation over a range of the particle sizes for each of the wavelengths, the first summation having the parameters, the scattering efficiency, and the mean cosine of scattering angle as arguments.

6. The method of claim 5, wherein said comparing includes performing a second summation over a range of the wavelengths, the second summation including a numerical difference between the first and second

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values as an argument.

7. The method of claim 5, wherein said changing includes updating the parameters as a function of the wavelengths, the first and second values, and a third value corresponding to mass of the particles.

8. A system for analyzing a number of particles suspended in a medium in sufficient concentration to multiply scatter light comprising:

a light source with a predetermined time-varying intensity configured to expose the medium to a number of different predetermined wavelengths of incident light;

a first sensor spaced apart from said source, said first sensor being configured to provide a first detection signal corresponding to detected light, the detected light being multiply scattered by the particles;

a processor responsive to the first detection signal and being configured to receive an exposure signal corresponding to said incident light, said processor being configured to generate: (a) a number of comparison signals each corresponding to a difference with respect to time between the detected light and the incident light for a corresponding one of the wavelengths, (b) a number of scattering signals each correspondingly determined from the comparison signals and each corresponding to an observed isotropic scattering coefficient of the medium for a different one of

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the wavelengths, and (c) an output signal indicative of one of size distribution or volume fraction of the particles, said output signal being determined as a function of said scattering signals; and

an output device responsive to said output signal to provide an output corresponding to the size distribution or volume fraction of the particles.

9. The system of claim 8, further comprising a reaction vessel containing the particles and medium, and wherein said output device includes a control element operatively coupled to said reaction vessel and responsive to said output to regulate a process involving the particles.

10. The system of claim 8, wherein said processor is further configured to determine said size distribution or volume fraction as a function of mass of the particles.

11. The system of claim 8, further comprising a second sensor providing a second detection signal, said comparison signals being determined as a function of said first and second detection signals for each of the wavelengths.

12 The system of claim 8, wherein said processor further determines a structure factor indicative of particle-to-particle interactions,

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said structure factor varying in accordance with concentration of the particles in the medium.

13. The system of claim 8, wherein said processor is configured to generate a particle interaction signal representative of particle-to-particle interactions that vary with particle concentration and influence light scattering behavior of the particles.

14. A system for analyzing a number of particles suspended in a medium in sufficient concentration to multiply scatter light, comprising:

(a) a light source with a predetermined time-varying intensity configured to expose the medium to a number of different wavelengths of light;

(b) a sensor spaced apart from the source, said sensor being configured to provide a detected light signal corresponding to multiply scattered light from the particles at the different wavelengths in response to exposure to said source;

(c) a processor responsive to said detected light signal, said processor including a calculation means for generating an output signal corresponding to at least one of particle size distribution or volume fraction in accordance with an observed isotropic scattering coefficient of the medium determined from said detected light signal, said calculation means including a means for iteratively determining a structure factor from an estimate corresponding to at least one of

said particle size distribution or said volume fraction, said structure factor being representative of particle interactions that influence light scattering behavior of said particles; and

(d) an output device responsive to said output signal to provide an output corresponding to at least one of said size distribution or said volume fraction.

15. The system of claim 14, further comprising a reaction vessel containing the particles and the medium, and wherein said output device includes a control element operatively coupled to said reaction vessel and responsive to said output to regulate a reaction involving the particles.

16. The system of claim 14, wherein said calculation means includes an estimating means for iteratively determining said size distribution or said volume fraction as a function of mass of the particles.

17. The system of claim 14, wherein said structure factor is dependent on said particle size distribution and said particle volume fraction, and corresponds to a P-Y hard sphere model.

18. The system of claim 14, wherein said calculation means includes a number of parameters corresponding to a Weibull distribution.

19. A method of particle analysis, comprising:

(a) exposing a medium with a number of suspended particles to a number of light wavelengths, the wavelengths each being intensity-modulated at a predetermined frequency;

(b) detecting multiply scattered light from the medium in response to said exposing to characterize propagation of the multiply scattered light through the medium with a number of values, the values each corresponding to a different one of the wavelengths and each being representative of at least one of a phase or an amplitude of the multiply scattered light relative to the predetermined frequency; and

(c) providing an output determined from the values, the output corresponding to at least one of a particle size distribution, particle volume fraction, or a particle interaction parameter, the particle interaction parameter corresponding to a nonlinear relationship between particle concentration and an isotropic scattering coefficient for the particles.

20. The method of claim 19, further comprising controlling a process in accordance with the output.

21. The method of claim 19, wherein said providing includes determining the observed isotropic scattering coefficient and an absorption

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coefficient for the particles for each of the wavelengths from a corresponding one of the values.

22. The method of claim 19, wherein said providing includes:

(i) determining an observed isotropic scattering coefficient for the particles for each of the wavelengths from a corresponding one of the values;

(ii) establishing an estimate corresponding to at least one of the size distribution or the volume fraction;

(iii) determining a calculated isotropic scattering coefficient for each of the wavelengths from the estimate;

(iv) comparing the observed and calculated isotropic scattering coefficients to establish an error;

(v) changing the estimate; and

(vi) repeating said calculating, comparing, and changing until the error reaches a desired minimum.

23. The method of claim 22, wherein said providing includes selecting the estimate to generally maintain mass balance of the particles, and the estimate corresponds to an expected form of the size distribution of the particles.

24. The method of claim 22, wherein the calculated isotropic

scattering coefficient is determined with an equation having an estimated product of the size distribution and the volume fraction as an argument.

25. The method of claim 19, wherein the particle interaction parameter is determined from a P-Y structure factor model.

26. A method of particle analysis, comprising:

(a) exposing a number of particles to a number of light wavelengths of predetermined time-varying intensity;

(b) detecting multiply scattered light from the particles in response to said exposing to determine a number of values each corresponding to a different one of the wavelengths, the values each being representative of a time-of-flight characteristic of the particles; and

(c) providing an output determined from the values, the output corresponding to at least one of a particle size distribution or volume fraction and being determined in accordance with a particle interaction parameter, the particle interaction parameter being representative of a nonlinear relationship between particle concentration and an isotropic scattering coefficient for the particles.

27. The method of claim 26, wherein the particles are suspended in a fluid medium and further comprising controlling a process in accordance with the output.

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28. The method of claim 26, wherein the particles have a concentration in the fluid medium of at least about 10% by volume.

29. The method of claim 26, wherein said determining includes calculating at least one of volume fraction and size distribution of the particles in the fluid.

30. The method of claim 26, wherein the particle interaction parameter is determined from the Percus-Yevick hard sphere model.

31. The method of claim 30, wherein said calculating includes adjusting the hard sphere model to account for forces between the particles.

32. A method of analysis, comprising:

(a) exposing a fluid to an incident light, the fluid having a number of suspended particles therein, the suspended particles being sufficiently concentrated in the fluid to scatter light;

(b) detecting multiply scattered light in response to said exposing to determine a time-based value characteristic of propagation time of the multiply scattered light through the fluid;

(c) determining a quantity as a function of the value, the quantity corresponding to an isotropic scattering coefficient; and

(d) providing an output corresponding to at least one of volume

fraction, particle size distribution, or a particle interaction parameter, the particle interaction parameter corresponding to particle-to-particle interactions influencing light scattering behavior of the particles, said providing including calculating a number representative of the isotropic scattering coefficient as a function of an estimate corresponding to the volume fraction and the size distribution.

33. The method of claim 32, further comprising controlling a process in which the particles are altered by utilizing the output as a feedback variable.

34. The method of claim 32, wherein said providing includes establishing an estimate corresponding to volume fraction and the size distribution and determining the particle interaction parameter as a function of the estimate.

35. The method of claim 34, further comprising constraining the estimate to maintain mass balance.

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36 ~~37~~. The method of claim 32, wherein the incident light is intensity modulated at a predetermined frequency, and said determining includes comparing the incident light and the scattered light to determine the value, and the value is representative of a relative phase or amplitude of the scattered light for the predetermined frequency.

37 ~~38~~. The method of claim ~~37~~ 36, wherein said detecting includes detecting the scattered light with a second sensor spaced apart from the first sensor by a separation distance and said determining includes calculating the quantity in accordance with the separation distance.

38 ~~39~~. The method of claim ~~37~~ 36, wherein said providing includes determining the volume fraction or size distribution in accordance with the diffusion equation for multiply scattered light.

39 ~~40~~. The method of claim 32, wherein the particle interaction parameter is determined from a P-Y structure factor model.

40 ~~41~~. A system for analyzing a number of particles suspended in a medium in sufficient concentration to multiply scatter light, comprising:

a light source configured to expose the medium to a number of

different predetermined wavelengths of incident light each having a predetermined time-varying intensity;

a first sensor spaced apart from said source, said first sensor being configured to provide a first detection signal corresponding to detected light, the detected light being multiply scattered by the particles;

a processor responsive to said first detection signal and being configured to receive an exposure signal corresponding to said incident light, said processor being configured to generate: (a) a number of propagation signals by comparing said first detection signal and said exposure signal for each of said wavelengths, said propagation signals each characterizing time of flight of the detected light through the medium resulting from multiple scattering by the particles for a corresponding one of said wavelengths, (b) a number of scattering signals each corresponding to an isotropic scattering coefficient of the medium and being determined from a corresponding one of said propagation signals, and (c) an output signal indicative of at least one of size distribution or volume fraction of the particles, said output signal being determined from said scattering signals and a structure factor, said structure factor accounting for particle-to-particle interactions influencing light scattering behavior of the particles; and

an output device responsive to said output signal to provide an output corresponding to said size distribution or said volume fraction of the particles.

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41 ~~42~~. The system of claim 40 ~~41~~, wherein said processor is further configured to determine said size distribution or said volume fraction as a function of mass of the particles.

42 ~~43~~. The system of claim 40 ~~41~~, further comprising a second sensor providing a second detection signal, said scattering signals being determined as a function of said first and second detection signals for each of the wavelengths.

43 ~~44~~. The system of claim 40 ~~41~~, wherein said structure factor corresponds to a P-Y hard sphere structure factor model.

44 ~~45~~. The system of claim 40 ~~41~~, wherein said processor further generates an absorption signal corresponding to an absorption coefficient of the medium and determines said absorption signal from said propagation signal.

45 ~~46~~. A method of particle analysis, comprising:

(a) exposing a number of particles to a number of light wavelengths of predetermined time-varying intensity;

(b) detecting multiply scattered light from the particles in response to said exposing to determine a number of time-based propagation

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characteristics of the particles each corresponding to a different one of the wavelengths; and

(c) calculating an observed isotropic scattering coefficient for each of the wavelengths from the characteristics;

(d) determining a calculated isotropic scattering coefficient for each of the wavelengths from an estimate of at least one of particle size distribution or particle volume fraction;

(e) comparing the observed isotropic scattering coefficient and calculated isotropic scattering coefficient for each of the wavelengths to establish and error;

(f) adjusting the estimate and repeating said determining and said comparing until the error reaches a desired minimum; and

(g) providing an output corresponding to at least one of the particle size distribution, particle volume fraction, or a particle interaction parameter.

~~47~~ 46. The method of claim ~~46~~ 45, wherein said determining includes establishing the particle interaction parameter as a function of the particle volume fraction and the particle size distribution.

~~48~~ 47. The method of claim ~~47~~ 46, wherein the particle interaction parameter corresponds to the P-Y hard sphere structure factor.

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48 ~~49~~. The method of claim 47 ~~48~~ 72/1, wherein the calculated isotropic scattering coefficient is determined with an equation having the structure factor and an estimated product of the size distribution and the volume fraction as arguments.

49 ~~50~~. The method of claim 45 ~~46~~, wherein the particles include liquid droplets dispersed in a fluid medium, the droplets and the medium having different indices of refraction.